Applications for Compact Portable Pulsed Power: Rocket Science, Cancer Therapy, and the Movies

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***Abstract*–This paper discusses aspects of a review presented in plenary session to the 26th Power Modulator Conference, May 2006, in Washington D.C. The goal was to present results from a Multidisciplinary University Research Initiative that focused on research into Compact Portable Pulsed Power, and to toss out a few ideas, looking ahead. The MURI was led by USC, with collaborators from the U. Missouri (Columbia) and Texas Tech University. The Conference was kind enough to encourage a presentation, after something rather similar, that is, a discussion of new applications and research issues for power modulators, presented to the conference 10 years ago (when it was called the Power Modulator Symposium). Hopefully, the results below will show some advancement in the numbers and diversity of applications reported a decade ago.**

I. INTRODUCTION

The talk presented what we think are highlights of research conducted under the Air Force Office of Scientific Research (AFOSR) Multidisciplinary University Research Initiative (MURI) in the area of Compact Portable Pulsed Power (CP^3). This program was created under the leadership of Dr. Robert J. Barker of the AFOSR. In fact, two CP^3 MURIs were initiated under Dr. Barker. One MURI has been led by the University of Southern California (Gundersen P.I.) in collaboration with Texas Tech University (J. Dickens) and the University of Missouri at Columbia (W. Nunnally). A second MURI has been led by the University of New Mexico (E. Schamiloglu P.I.) in collaboration with Old Dominion University (K. Schoenbach) and the University of Nevada at Reno (R. Vidmar), and is discussed in a companion paper authored by Dr. Schamiloglu and his colleagues. There has been a strong interactive research atmosphere between the two MURIs, and collaborative work also fostered productive research in other areas, including bioelectrics and flame ignition, stimulating interest and collaborations with other researchers including the Naval Postgraduate School, Wright Patterson Air Force Research Laboratory, Stanford, U. Cincinnati, Cedars-Sinai Medical Center, and others.

In keeping with the theme of the talk presented to the Power Modulator Symposium in 1996 [1], the emphasis is on the innovations that show particular promise for *the applications of* repetitive pulsed power modulators. Some of these include:

1) Research into ultra-high power architectures using the back-lighted thyratron (BLT) – a super-emissive cathode, or pseudospark-type switch. Outcomes of these basic studies showed potential for robust and reliable repetitive operation, with very high voltage and peak current, and include basic studies that have demonstrated high voltage operation of extremely compact "mini-BLT" switches.

2) Applications to flame ignition and detonation, including ignition of pulse detonation engines (PDE). Using fast-rising pulses lasting <100 ns, obtained with the advanced repetitive pulsed power, plasma in a formative phase is produced and applied for ignition of fuel. This approach allows volume ignition with low energy cost, production of electronically excited species, and considerably reduced delay to ignition – resulting, for PDE, in the enabling of higher operational repetition rates (in testing at Navy and Air Force laboratories and several universities) and other benefits.

3) Studies of nanosecond pulsed electric fields for the induction of apoptosis (programmed cell death) in cancer cells *in vitro* and tumors *in vivo*. This work involves integration of (micro) pulsed power with fluorescence microscopy for studies of the effects of intense nanosecond electric fields on various cancer cell lines. In addition, animal studies conducted with catheter-based pulsed power delivery systems are showing Promise for potential therapies for pancreatic, melanoma, and other cancers. Work in this area is presented in more depth in the conference presentations, and in the short-course by Prof. Schoenbach at the end of the PMC.

Finally, a project (tenuously connected to pulsed power in the presentation) to foster and encourage improved portrayals of science in film is briefly discussed. This project derives from projected needs for scientists and engineers in the future. Goals include stimulating interest in science and engineering in children, and improving perceptions of science in society. Innovations include workshops at the American Film Institute for teaching scriptwriting and other aspects of the film industry to scientists and engineers.

II. MINI-BLTS FOR MODULATORS

The pseudospark (the optically triggered version of this switch is referred to here as a Back-Lighted Thyratron

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(BLT) [2]) is a low pressure (typ. 0.1-0.5 torr hydrogen), uniform glow discharge switch [3] with high hold off voltage. The switches are related to hydrogen thyratrons, with, however, a different cathode physics. They conduct 5-10 kA in simple demountable or hermetically sealed configurations. Much higher current has also been switched [4].

The cathode emission is distinguished from a hydrogen thyratron by an initially cold cathode that is self-heated, and thus does not require an external heater. This simplifies housekeeping, as the complexity of the external cathode is eliminated, and the size, due to an extraordinarily high emission characteristic, is vastly reduced. The physics of this process includes an intriguing super-emissive mode of cathode operation [5]. Lifetimes in excess of 10^8 pulses have been reported [6].

Because of its potential for reducing size, weight, and complexity, CP^3 has studied the BLT, and smaller versions, referred to as "mini-BLTs", for very high power, short pulse operation, and for implementation into voltage multipliers such as Marx bank configurations of pulse generators [7, 8]. Photographs of the BLT, and the mini-BLTs, are shown in Fig. 1. In work reported at this meeting, the mini-BLT has been shown to operate reliably at 40 kV hold-off, with current to approx. 10 kA [9]. The results suggest that there is considerable potential for compact pulsed power applications.

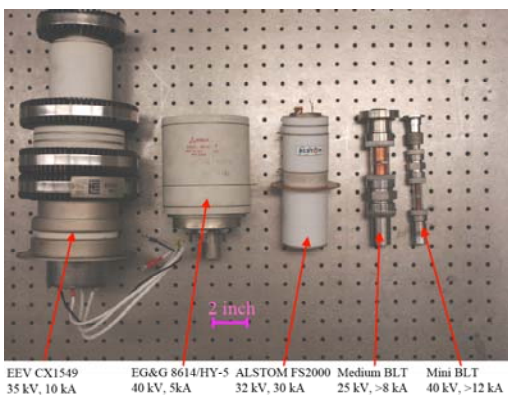

Fig. 1. Various thyratron, pseudospark and BLT switches. The grid on the background table is 1 inch. The small BLT at the right is 12.5 mm diameter, holds off ≈40 kV, has fast rise time, is optically triggered, and conducts ≥10 kA. Apart from size and housekeeping, key differences in operational characteristics include lifetime: the mini-BLT has operated for a few million pulses without diminished performance – performance to end-of-life remains to be determined; thyratron life, when operated within spec, can exceed 10^9 shots. Rise-time tends to be faster in the BLT and pseudospark, because of inductance related to the simple geometry.

Fig. 2. 3-stage pseudospark Marx bank.

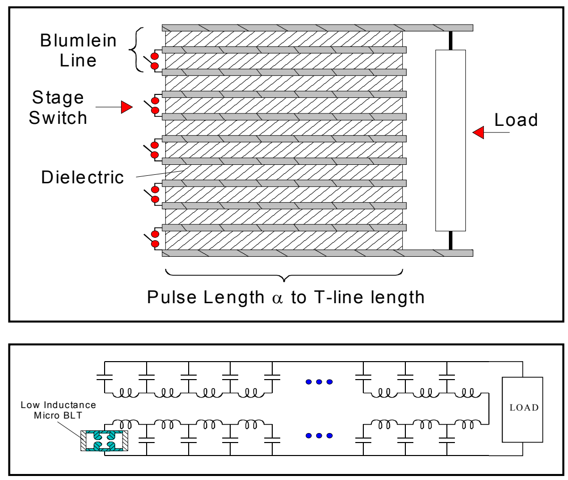

Fig. 3. Stacked Blumlein configuration. Below: Lumped line with small BLT switch. (Courtesy W. Nunnally)

Fig. 2 shows a Marx bank comprised of pseudospark switches, used for studies conducted in collaboration with TTU colleagues J. Dickens and A. Neuber. In these studies, a 3-switch Marx bank was fabricated and tested using commercial versions of the pseudospark purchased from Alstom. The Marx was operated at 90 kV, switching 10 kA with a 1 μsec pulse. Future work is planned to implement the optically-triggered mini-BLT in this configuration.

Work at the University of Missouri under the direction of Prof. Wm. Nunnally has studied optimal volume for the pulse modulator, with focus on stacked and multiple Blumlein pulse generators. This work considers energy density in a stacked blumlein configuration. A schematic of such a modulator is shown in Fig. 3, which also shows a configuration employing a small BLT switch. This work has also investigated SiC photoconductive switching for fast, efficient pulse generation. These integrated systems are a promising pathway to optimize weight, volume and performance.

III. APPLICATIONS TO FLAME IGNITION AND DETONATION FOR ROCKET ENGINES

Recently it has been reported that reduction in delay to ignition, leaner burn operation, and other desirable aspects of flame ignition are obtained when applying a very short pulse that generates an array of streamers, distributed over a macroscopic volume [10]. Such pulses have now been used to achieve detonations with reduced delays in a number of pulse detonation engines (PDE), for example, in experiments at the Naval Postgraduate School Rocket Propulsion Laboratory, Wright Patterson Air Force Research Laboratory, and Stanford University [11]. These applications required pulse generators capable of fast risetime pulses, for pulse lengths typically 50 ns or less.

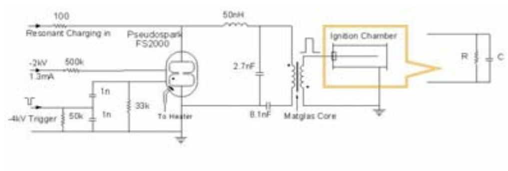

Fig. 4. Line-type pulser with pseudospark switch connected to ignition chamber for flame ignition studies.

Utilizing research supported by the AFOSR, pseudospark-based pulse generators were developed for these applications. These pulse generators produced 50 ns pulses reliably with 90 kV output to a combustion chamber with time varying load impedance. A typical schematic is shown in Fig. 4.

It was found that the pseudospark enabled improving the repetition rate of the PDE, and served well as laboratory-research pulse generators in a number of research laboratories. A typical output voltage and current, measured at the reactor, is shown in Fig. 5. Fig. 6 shows a pulse detonation engine configure for transient plasma ignition with a pseudospark-based pulse generator. Studies at NPS showed a 5-fold reduction in delay to detonation with this approach [12]. A number of new applications are envisaged for combustion.

IV. APPLICATIONS TO NANOSCALE BIOLOGY AND TO CANCER THERAPIES

Several new generations of ultra-compact pulse generators for biological applications have been developed. For in vitro studies, a microscope stage assembly has been developed that integrates pulse generator, microchamber, and microscope (Fig. 7, [13]). Studies of nanosecond pulse cell electroperturbation require high-voltage nanosecond pulses delivered to low-impedance electroporation cuvette loads, and to small chambers integrated into optical systems such as microscopes. Pulsed power work has required the design and operation of such pulse generators. In one example, a pulse generator based on series and parallel connected ordinary rectifying diodes as an opening switch.

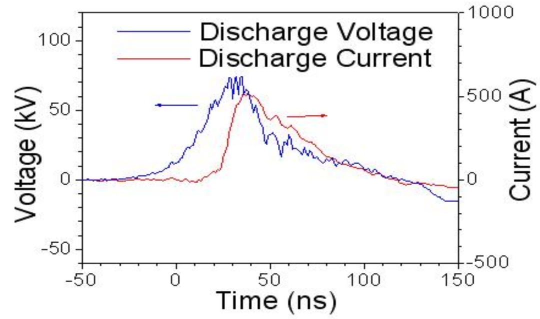

Fig. 5. Pseudospark pulse generator voltage and current applied to ignition reactor. For optimal operation current is approximately in phase with voltage for these applications.

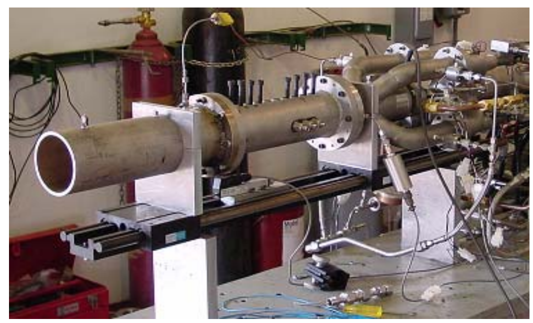

Fig. 6. Pulse detonation engine at the Naval Postgraduate School Rocket Propulsion Laboratory.

The generator produces 5 ns wide, 10 kV amplitude pulses into a 10 Ω cuvette load at the maximum repetition rate of 1 kHz. The design incorporates a primary IGBT switch. Pulses produced by the IGBT are compressed by two low-loss, nanocrystalline, saturable core compression stages. The compressed pulses are fed to the diode opening switch through a fast, ferrite saturable core transformer. Various other versions of these truly compact pulse generators have been reported [14]. Details of biological studies are reported elsewhere [15,16, 17] – the discussion here emphasizes the usefulness to these diverse areas of innovation in pulse generator design.

The compact pulsed power was further developed into an apparatus appropriate for in vivo studies. Results of these studies have now shown potential for therapeutic applications to human cancer tumors, including melanoma, and pancreatic cancers [18].

V.THE MOVIES

In the presentation I showed an example of a movie with a lack of verisimilitude involving pulsed power – to provide a path to a project that we are pursuing that involves entertainment (movies) and education. This area is

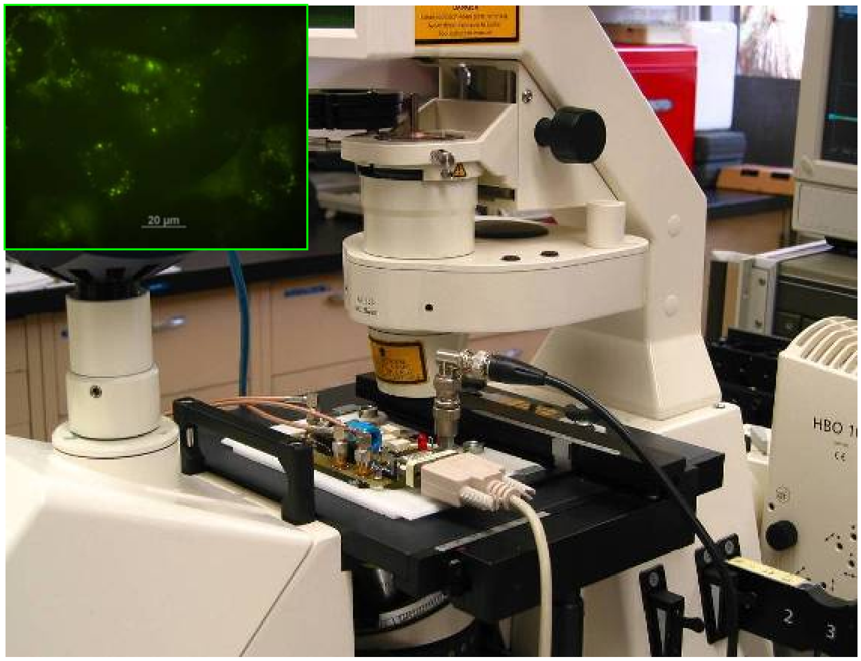

Figure 7. Inverted microscope with pulsed power-microscope integration. Inset: quantum dots in pulsed ovarian cancer cells, 20μm scale. See P.T. Vernier, Y.S. Lin, T. Black, C.H. Liang, M.T. Chen, T. Tang, L. Marcu, and M.A. Gundersen., "Biophotonic studies of mammalian cells with nanosecond pulsed power power," this meeting.

Fig. 8. Directors with extensive experience in film and television, Alex Singer and Martha Coolidge, teaching at the 2004 AFI Catalyst Workshop (for a report, see *Nature*, Vol. 430, p 770, 2004). Coolidge is also past president of the Directors Guild of America.

important to our field, and to other fields in engineering and science, because of future needs in these areas as well as the aesthetic value of science in our lives. Some years ago I was given an opportunity to work on a science-oriented comedy feature film, "Real Genius", which provided an introduction to many interesting aspects of the film industry, not the least of which were colleagues and friends that have developed since that time. Among the more interesting problem areas that emerged were the issues related to education, and the role that entertainment plays in teaching. This problem is especially important to engineering, given such things as concerns over the numbers of engineers that graduate and are preparing for careers that are of value to the technological innovation in the U.S. and abroad [19].

In discussions with colleagues in the industry, including Martha Coolidge, Alex Singer, and Joe Petricca of the American Film Institute (AFI), and with scientists and engineers, including Bob Barker of the AFOSR, Bill Wulf of the National Academy for Engineering, and with many others, an idea was formed to initiate workshops that would introduce interested scientists and engineers to the creative process in movies and television. This led to the Catalyst project. This project has created several workshops conducted at the AFI, and has initiated other activities. There are a number of reports of the workshops in the popular media [20]. This summer 2 workshops are being conducted at the AFI, one for high school students, and one for scientists and engineers.

It is clear from the concerns that have been raised from many different directions that this is an extraordinarily important area for further work. Of the research projects described above, however, this is the most difficult, perhaps because it requires so many different disciplines, and requires stepping so far out of the box. The entertainment industry can benefit from association with science – programs such as "Numbers" and "CSI" are indicating this, and innovative documentaries on PBS, National Geographic, and other channels are also showing. It is clear to me that many professionals in the entertainment industry are 1) very bright, and 2) have an appreciation of the importance of the problems in education. It is an important mission to work on all levels to stimulate our children's interest, and encourage appreciation of these innovative programs.

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